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Design and Wind Tunnel Testing of a Thick, Multi-Element High-Lift Airfoil

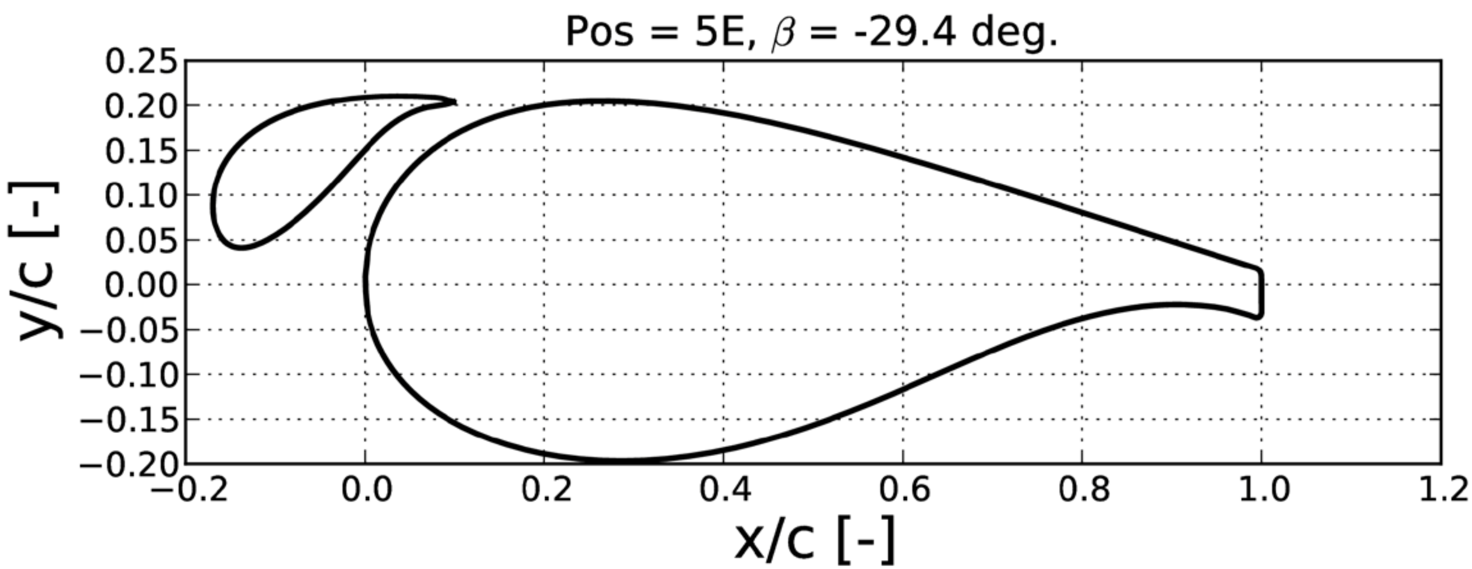
Frederik Zahle, Mac Gaunaa, Christian Bak, Niels N. Sørensen

Wind Energy Department · DTU

EWEA 2012 Annual Event
Copenhagen, Denmark, 16-19 April 2012

Background: What is a multi-element airfoil?

A multi-element airfoil typically consists of two or three elements. One main element, and a leading edge slat and/or flap.



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Background: Why thick high-lift airfoils?

We want to increase the aerodynamic loading close to the root

Increasing the loading in the root area of a turbine ($0.1 < r/R < 0.25$) can increase *AEP* by $\sim 1\%$ (see Poster 303).

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How do we achieve the necessary aerodynamic loading?

- Increase airfoil chord,
- Vortex generators,
- Flatback airfoils, Gurney flaps, divergent TEs etc,
- Multiple element airfoils.

Background: Why thick high-lift airfoils?

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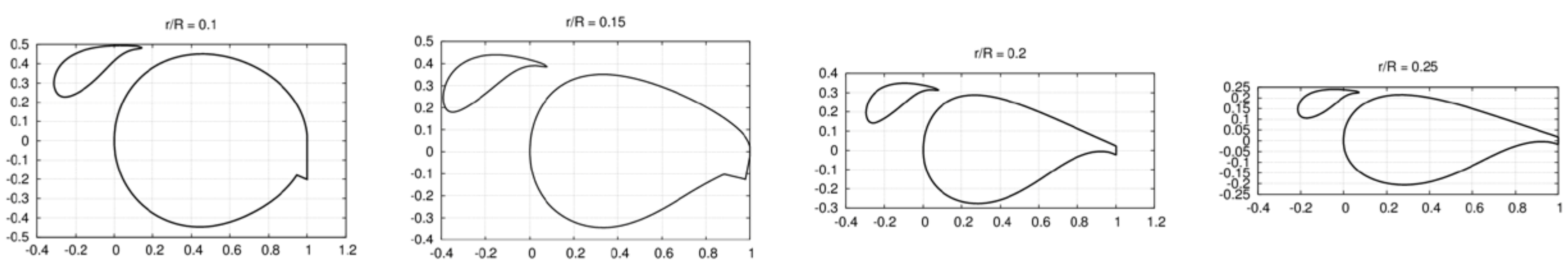
How do we achieve the necessary aerodynamic loading?

Leading edge slats

- Multi-element airfoils can produce high lift coefficients (>3) even with very thick airfoil sections.
- With very high lift coefficients the chord can potentially be reduced.



This work

The aim

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The airfoil

- Two elements: Main airfoil and a slat.
- 40% thick main flatback airfoil, 30% chord slat.
- Lift coefficient > 3

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This presentation

- Presentation of the designed multi-element airfoil.
- Wind tunnel setup.
- Comparisons of numerical results and wind tunnel measurements.
- 3D tunnel effects.

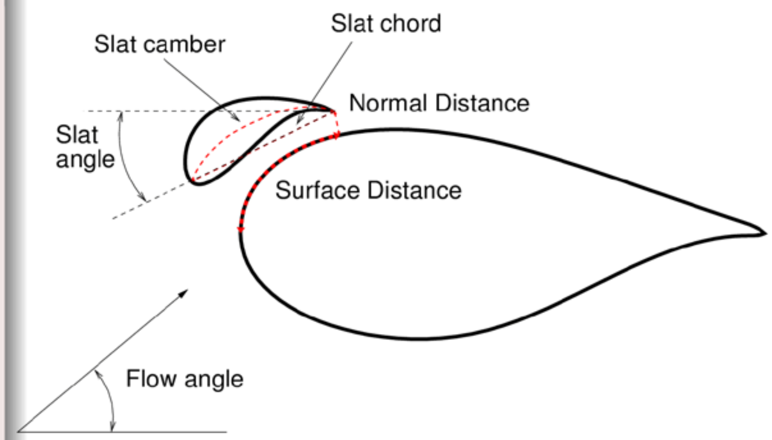
Leading edge slat optimization

Design Method

- Optimized using a Matlab optimizer, `fminbnd`.
- Automized mesh generation using HypGrid2D.
- Incompressible CFD solver EllipSys2D.

Design Variables

- Angle of attack,
- Position of slat trailing edge measured as:
  - Surface distance along main aerofoil surface from LE,
  - Normal distance from main aerofoil surface to slat TE.
- Slat angle relative to main aerofoil.
- Slat camber (parabolic curve).

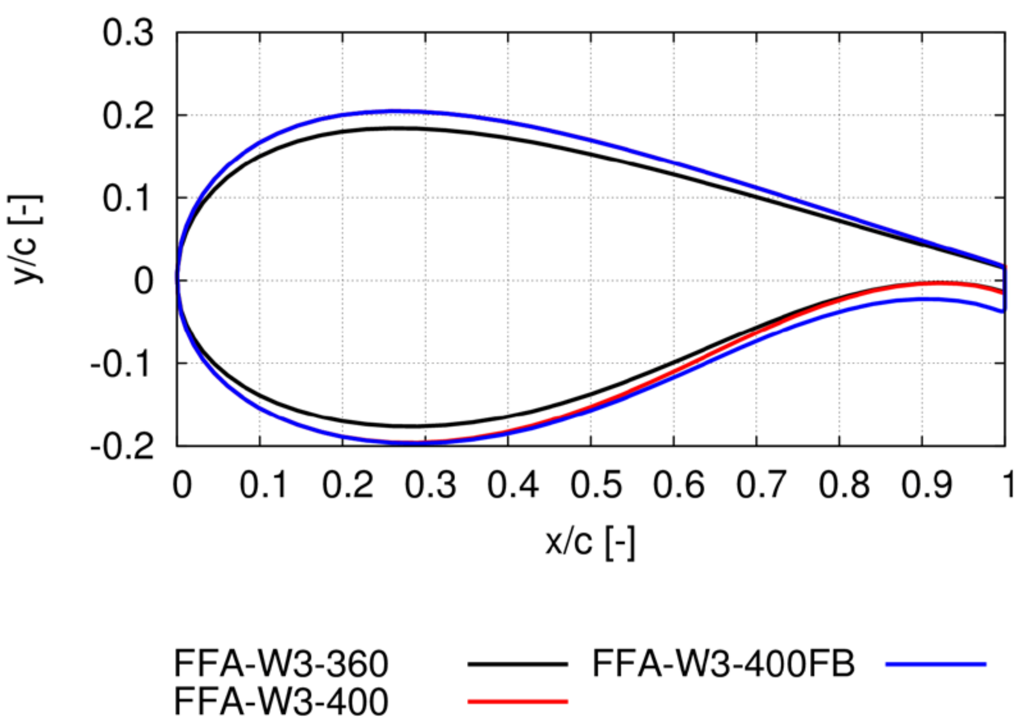


Results

Flaback Airfoil

The present study is based on the FFA-W3-360 aerofoil which was modified in the following manner:

- Increased thickness from 36% chord to 40% chord,
- Opening of trailing edge from 3.6% chord to 5.6% chord.



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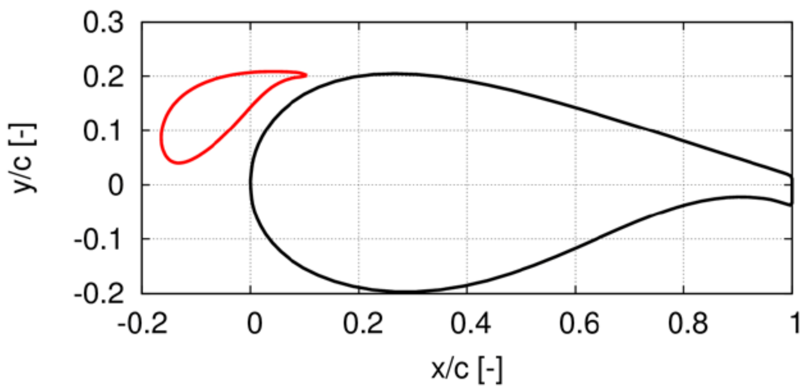
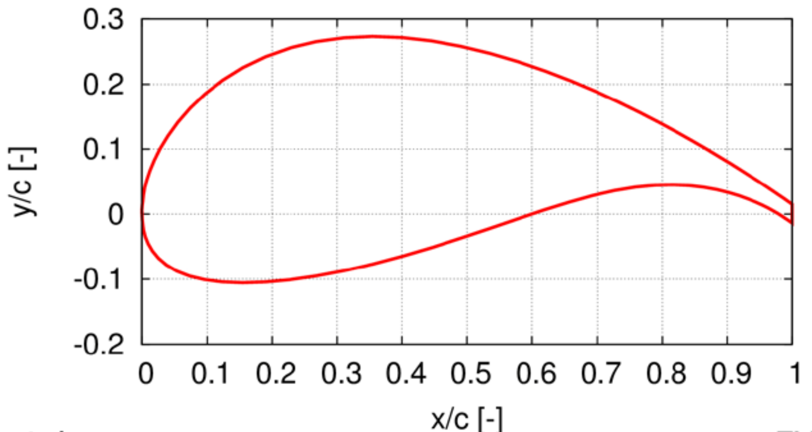
Slat Optimization - final design

The leading edge slat was also based on the FFA-W3-360 aerofoil. The final design is shown below.





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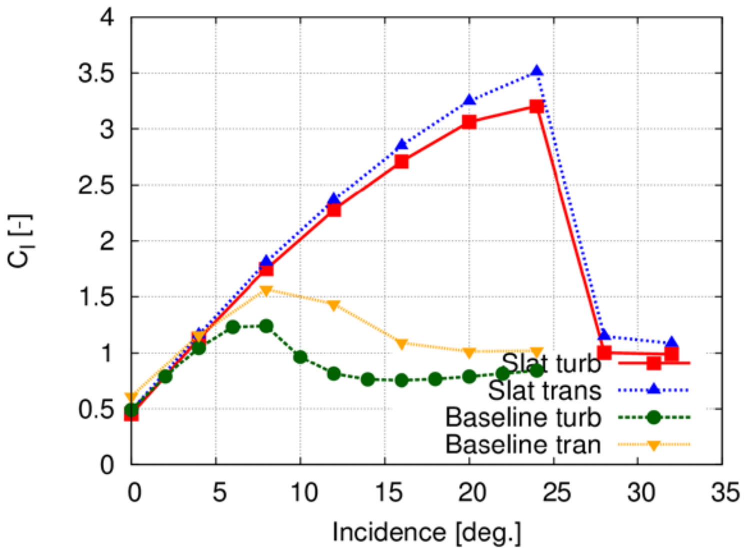
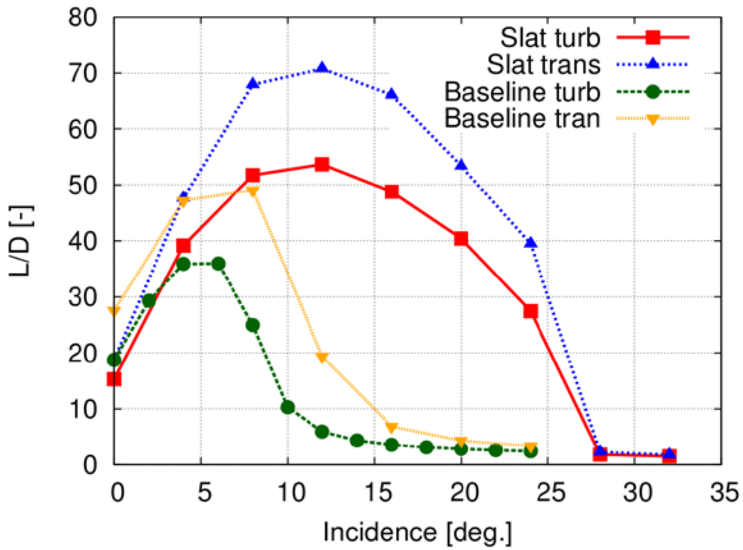
Results

Predicted Slat Performance

2D lift coefficielt and lift to drag ratio as function of incidence for fully turbulent and transitional boundary layers.





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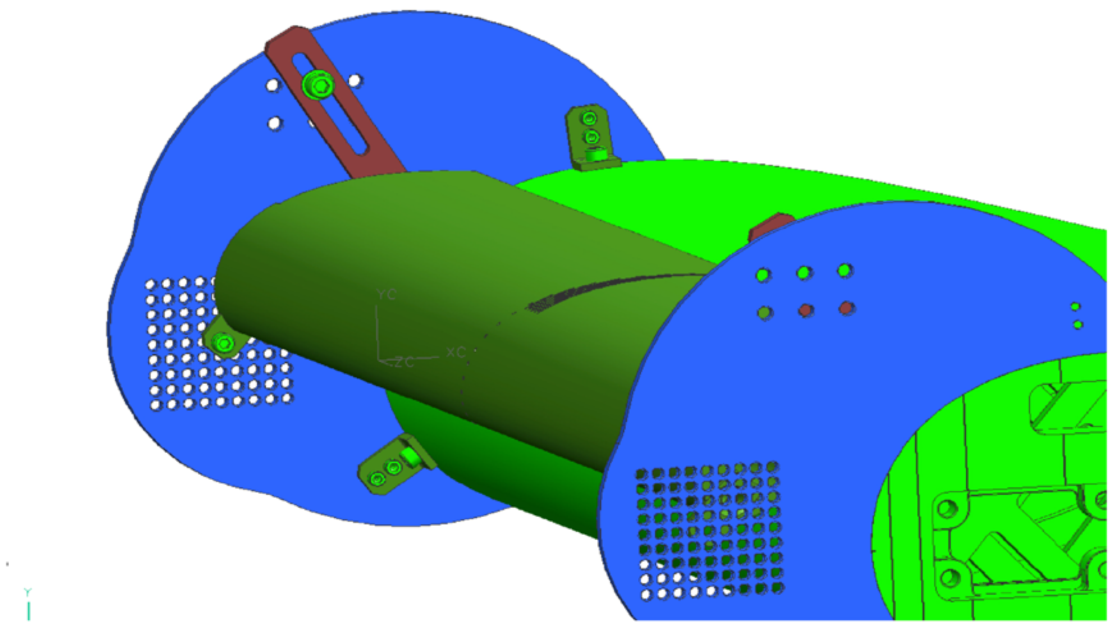
Wind Tunnel Setup

Test setup designed by LM Wind Power.

- The slat was hinged at it's leading edge.
- Could be moved within limits of a grid with 8×8 holes with 10 mm spacing.
- Slat angle β could be changed steplessly.



Wind Tunnel Experiment Plan

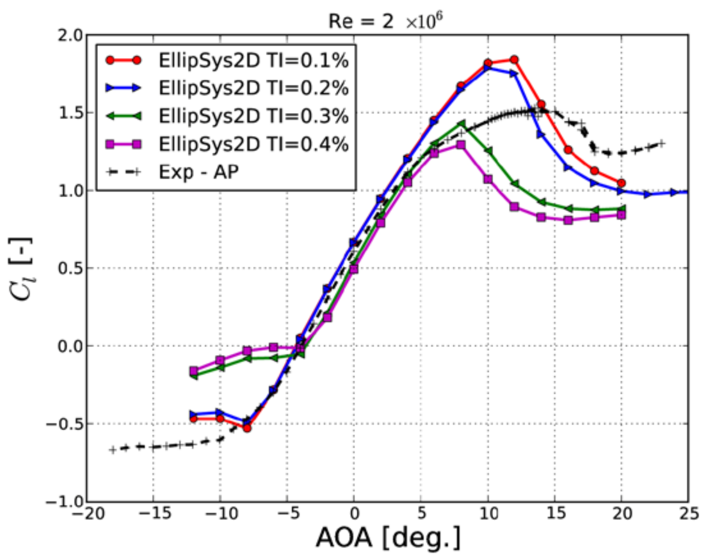
A comprehensive test plan

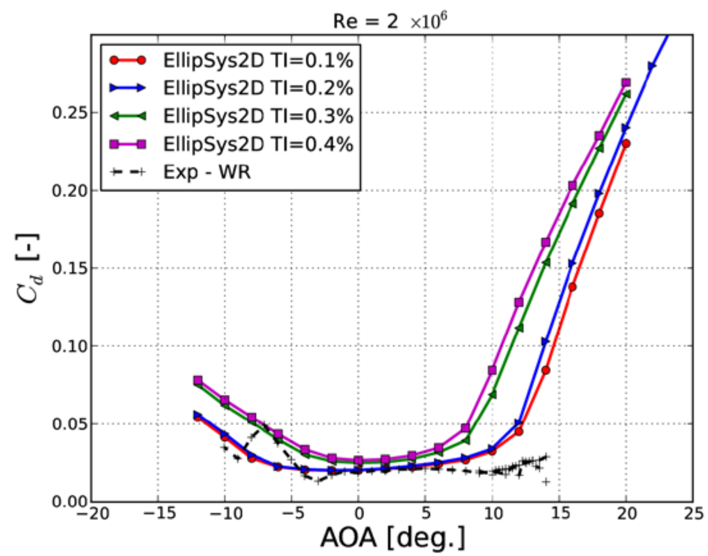
- The wind tunnel campaign was split into two parts:
- Flatback airfoil:
  - Clean, four Reynolds numbers: 1, 2, 3 and 4×10^6,
  - Roughness, Vortex generators, Gurney flaps.
- Slatted airfoil:
  - Clean, four Reynolds numbers: 1, 2, 3 and 4×10^6,
  - Seven slat positions,
  - Slat angle variations at five positions,
  - Roughness, Vortex generators, Gurney flaps at slat one position.
  - Flow visualization using wool tufts.

Isolated flatback airfoil

Comparison to EllipSys2D

- EllipSys2D simulations predict large variation in performance as function of turbulence intensity (TI).
- Good agreement with experiment for AOA $<$ 5 deg, poor agreement at high AOA.

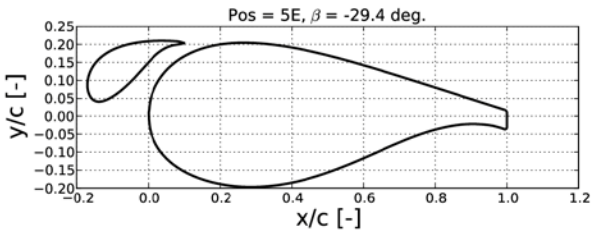


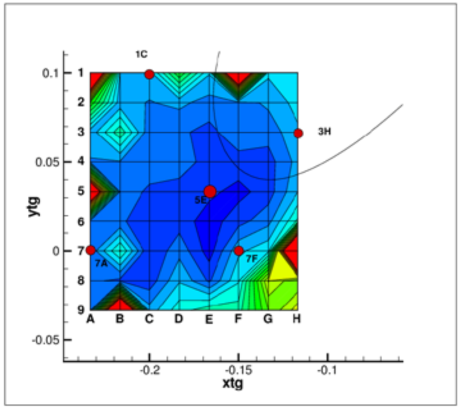


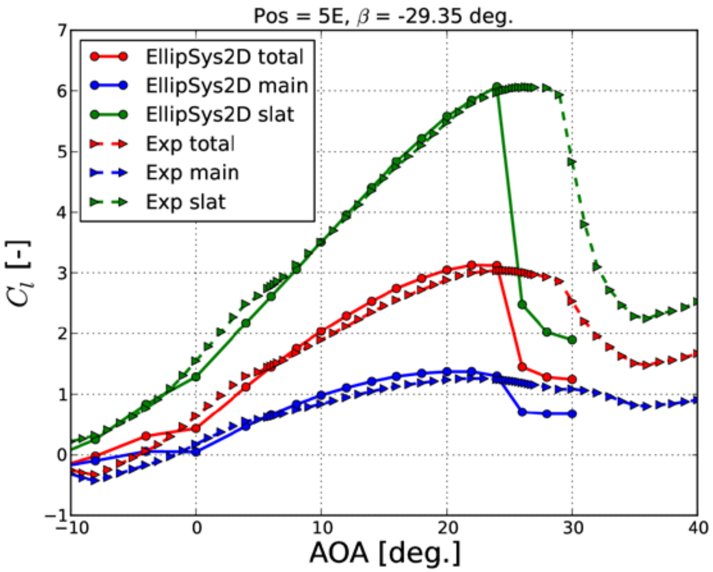
Flatback with slat airfoil

Reference position 5E

Position 5E with reference β=-29.35 deg. showing contributions from main, slat and total (slat C_l normalized with slat chord). TI = 0.2%







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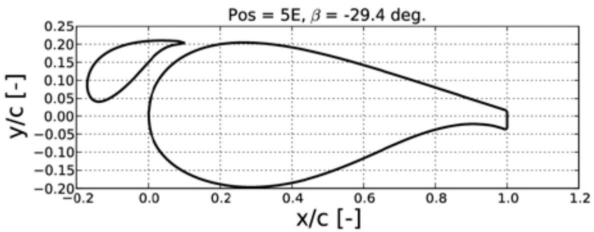

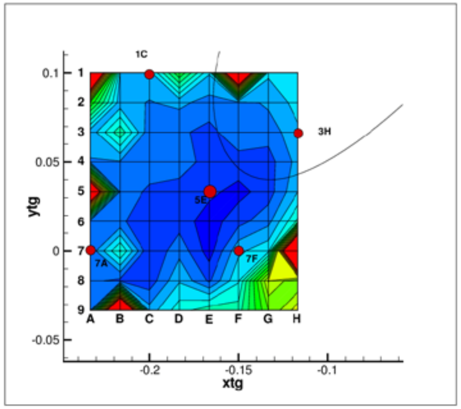

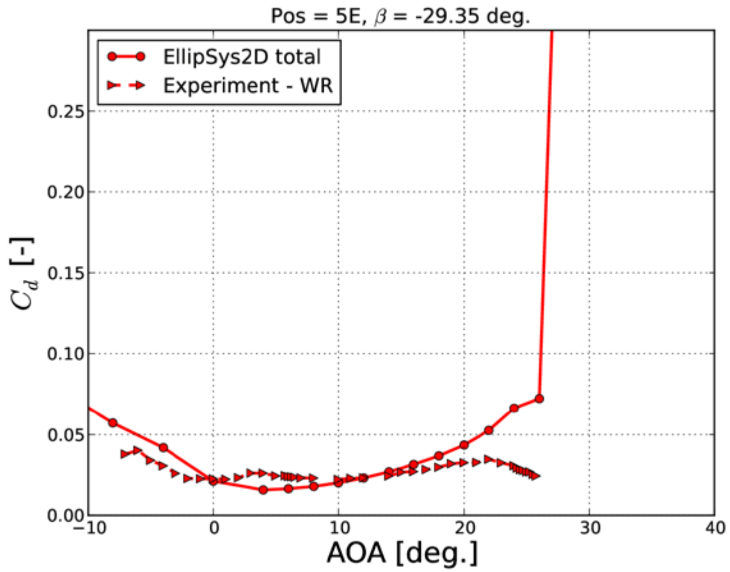

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Results
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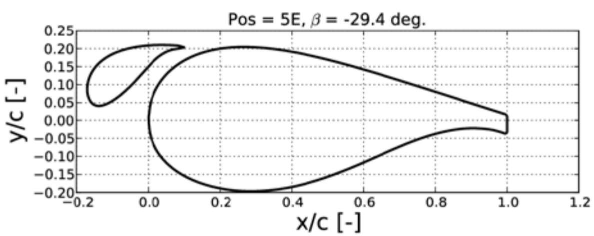

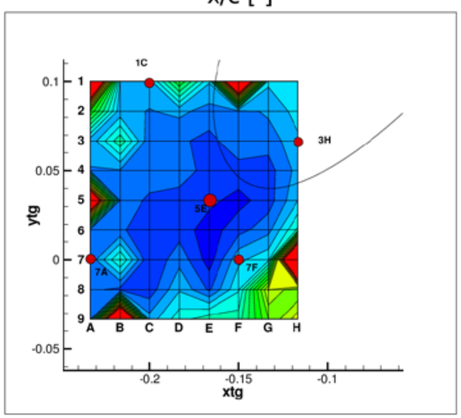

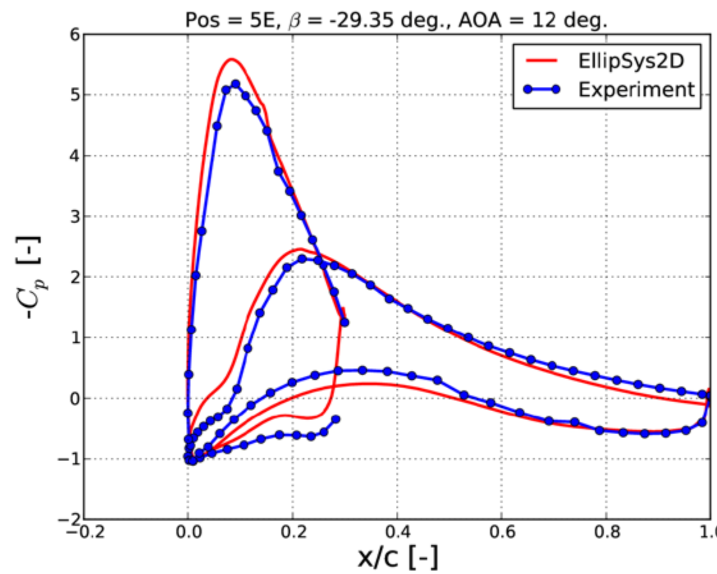

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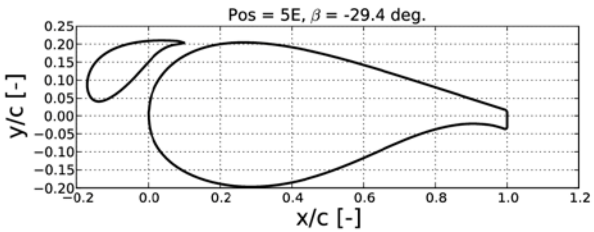

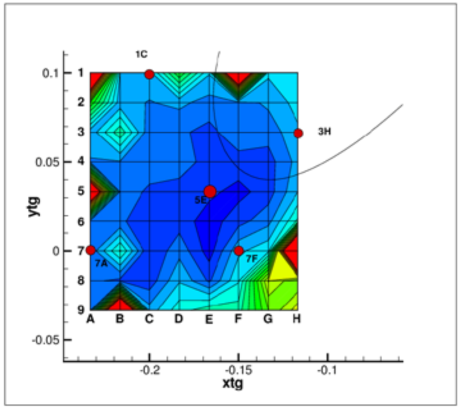

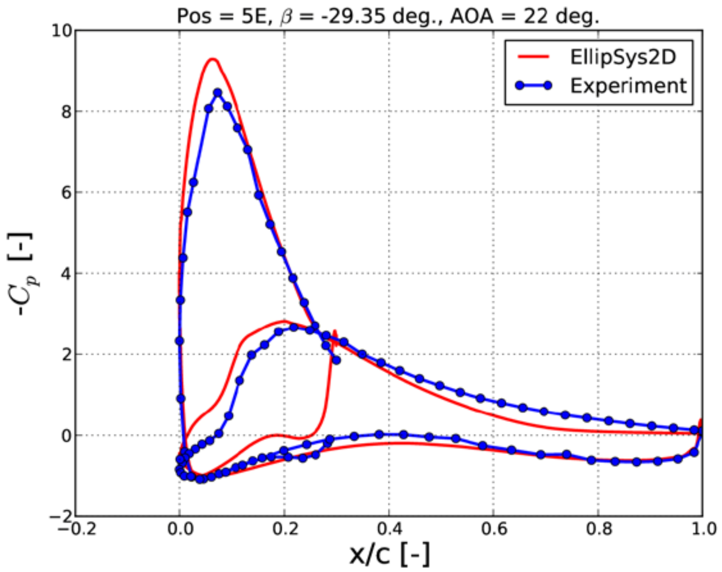

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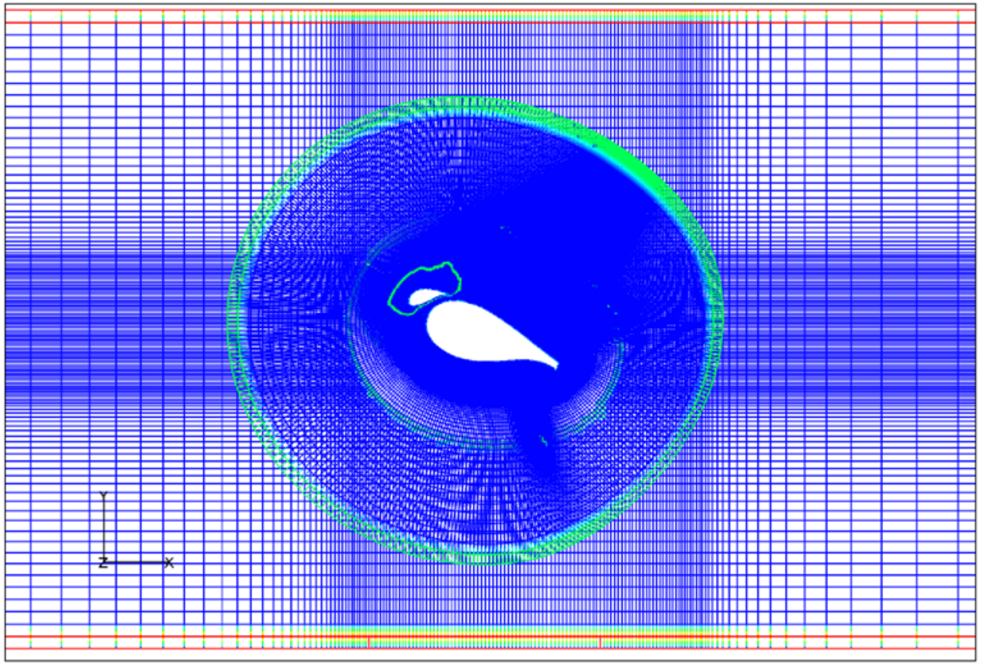
Wind Tunnel Results
Flatback with slat airfoil

2D Tunnel Effects

- 2D simulations were carried out using a wind tunnel setup with symmetry conditions on top and bottom walls.
- 2D simulations with same airfoil grids but with outer mesh boundaries placed 30c away from airfoil made for comparison.



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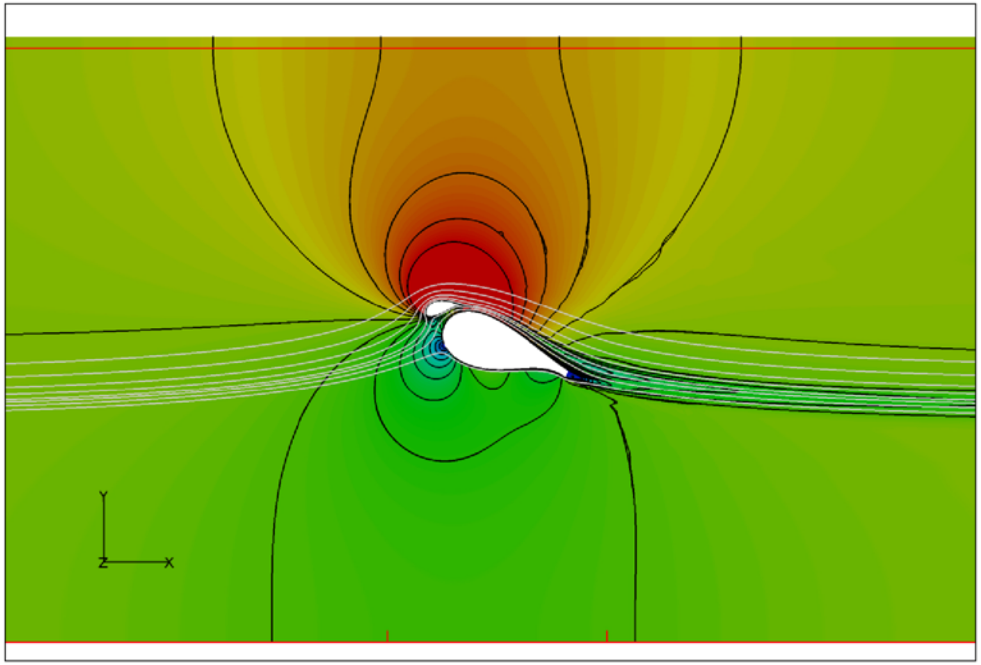

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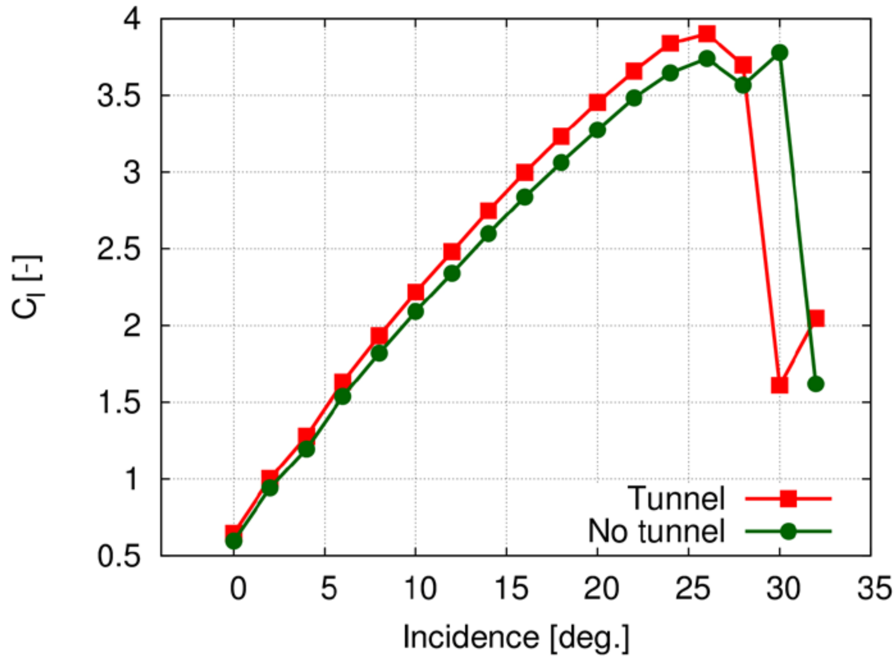
- Drag coefficient is largely unchanged.
- 2D tunnel effects cannot explain the discrepancies seen between simulations and measurements.



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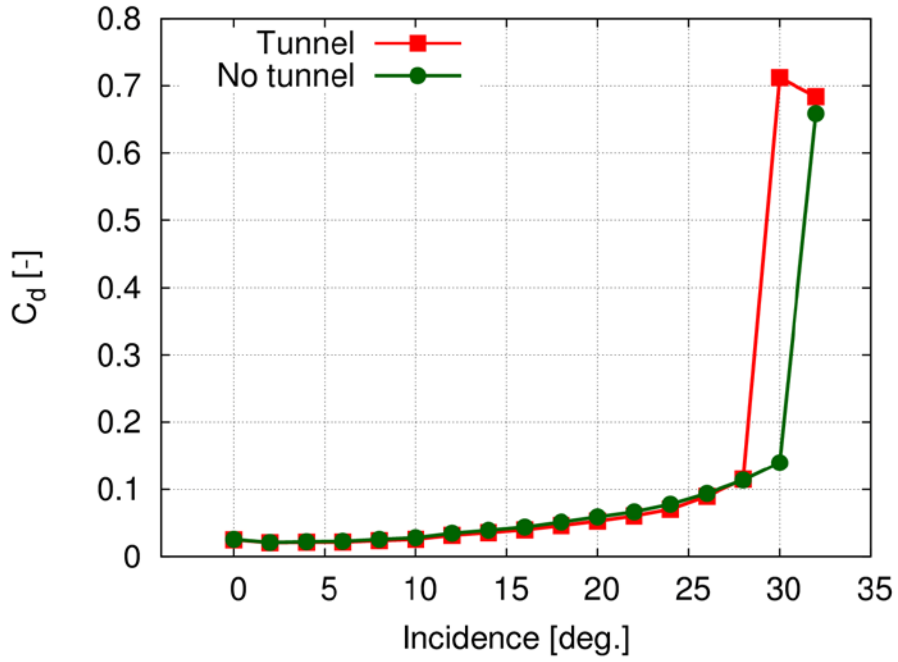

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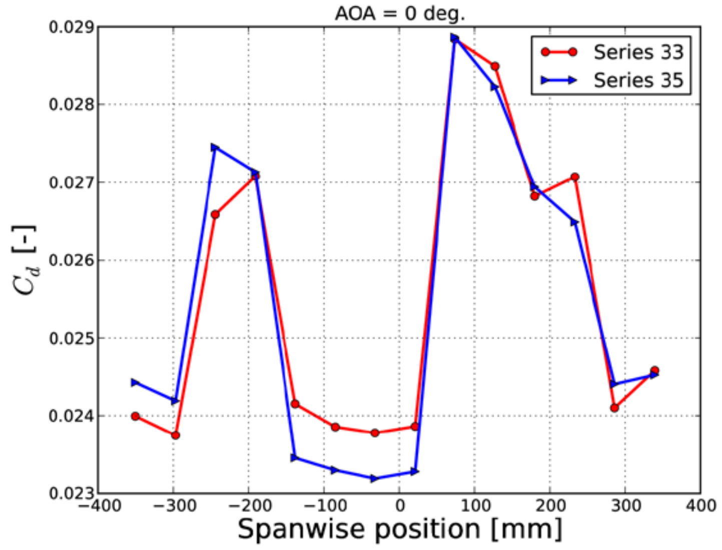
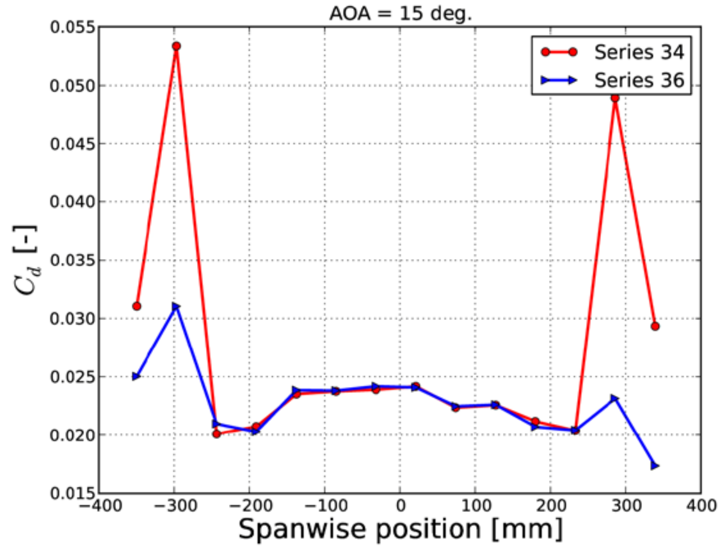
Flatback with slat airfoil

3D Tunnel Effects - wake rake traversal

Drag coefficient as function of lateral measurement position for the multi-element airfoil with the slat in position 5E tested at $Re=2\times10^6$. 0 mm is the center of the tunnel. The total tunnel width is 1400 mm.





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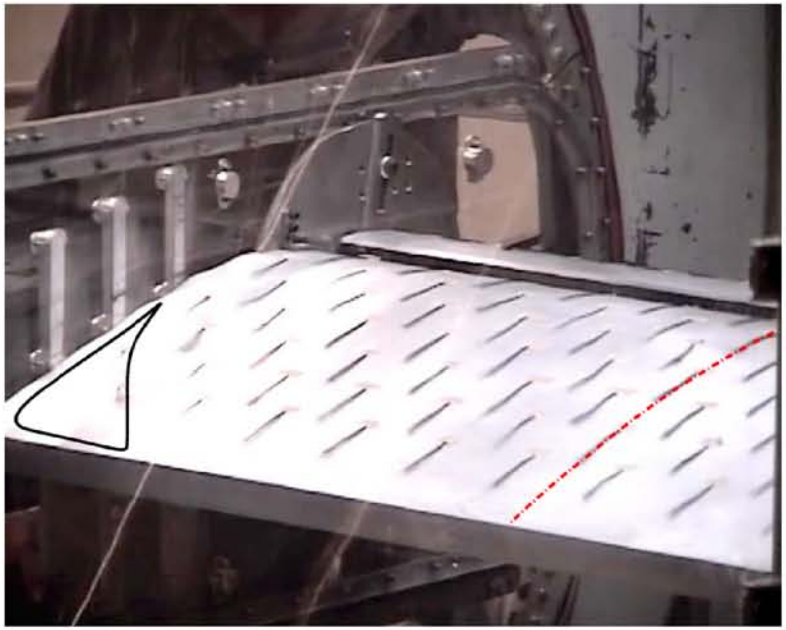
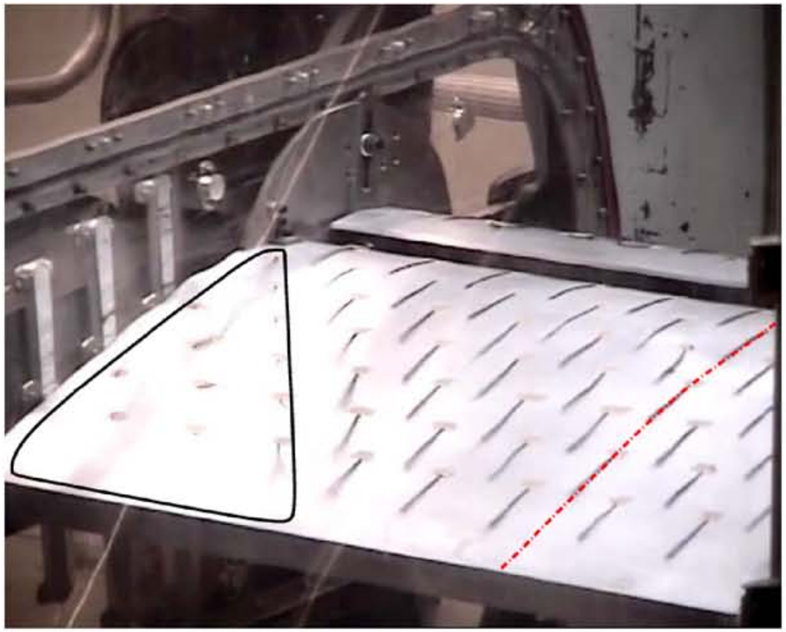
Flow Visualization

3D surface flow

- Flow visualization using tufts revealed 3D effects caused by wall effects even at low AOA.
- Below pictures are from AOA=0, 5, 15 and 24 deg.





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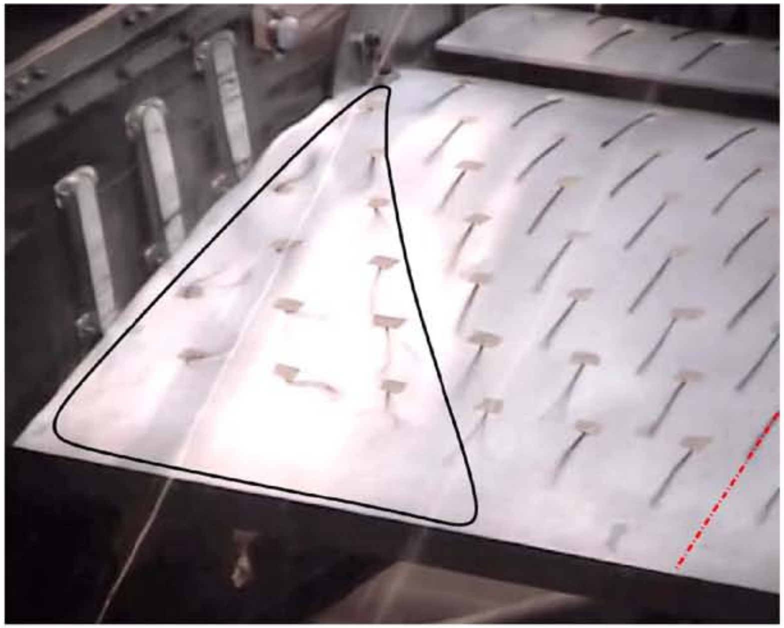

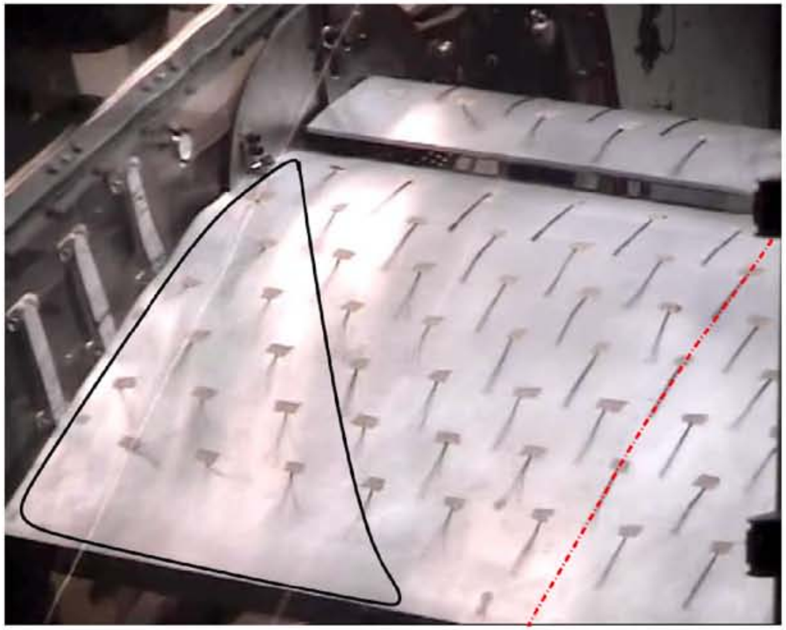

3D CFD on a Wind Tunnel Configurations

Wall Interference Effects

- 3D CFD simulations by Niels N. Sørensen on an FB-3500-1750 flatback airfoil show similar trends when comparing simulations with and without walls.
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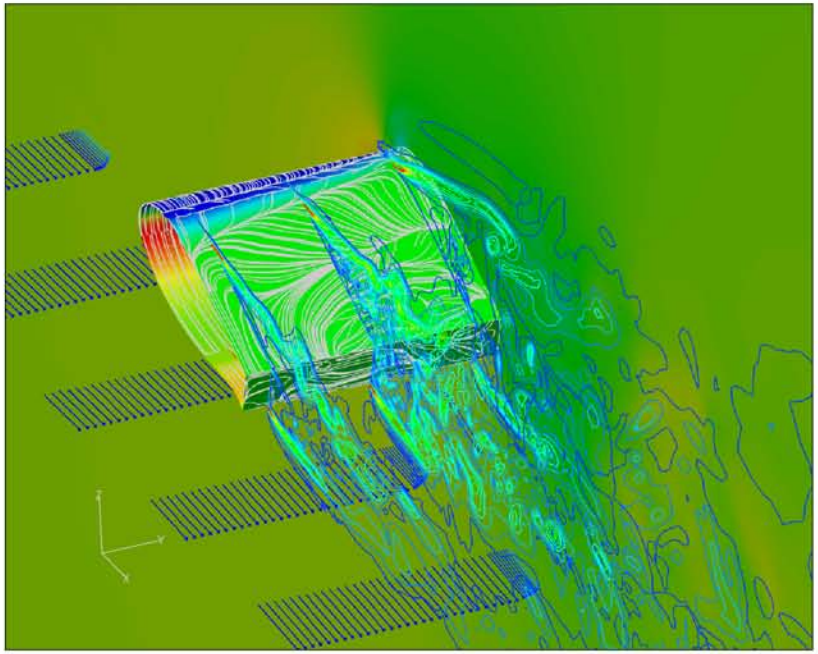

Wind Tunnel Results
3D CFD on a Wind Tunnel Configurations

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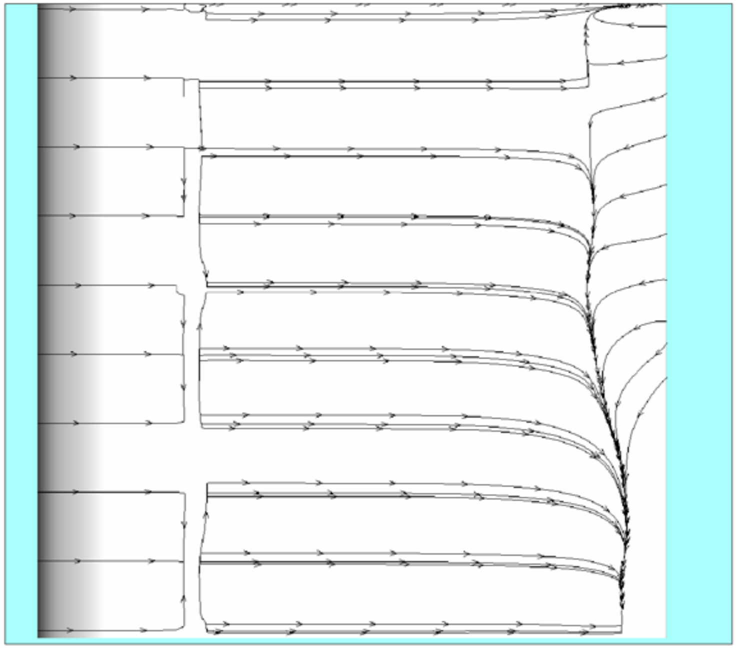

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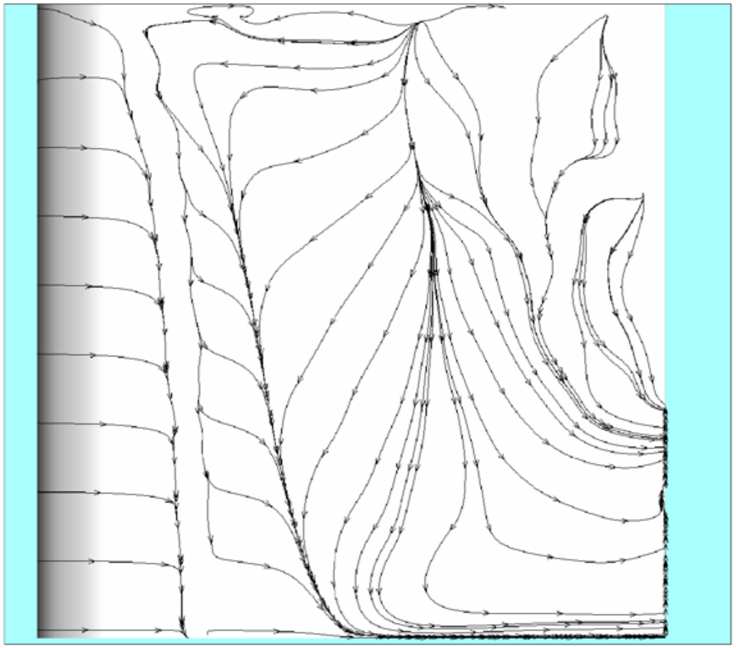

Conclusions

Design of a high lift, thick, flatback, multi-element airfoil

- A 40% thick flatback with a 30% chord slat airfoil was designed that was predicted to have a C_{l-max}=3.4.
- Geometry based on 'open source' airfoil.

Conclusions

Design of a high lift, thick, flatback, multi-element airfoil

Wind Tunnel Campaign

- The multi-element airfoil was tested in the LM Wind Power wind tunnel.
- Comprehensive test matrix, data still being processed.
- Analysis of the results revealed what was believed to be severe 3D effects.
- Flow visualization and wake rake traversal confirmed this.

Conclusions

Design of a high lift, thick, flatback, multi-element airfoil

Wind Tunnel Campaign

CFD Comparison

- Consistently good agreement between computed and measured slat lift.
- Computations predicted earlier main aerofoil stall than measured.
- 2D tunnel effects did not account for discrepancy between computations and measurements.
- 3D CFD results indicate that wall effects can be significant on thick airfoils at high angle of attack.

Future Work

Wind tunnel testing

- We need to improve measurement methods for thick airfoils to reduce wall interference effects.
- Are effects of compressibility at play?

Future Work

Wind tunnel testing

Airfoil Optimization

- Improved optimization framework based on GTO (also used in AirfoilOpt) and OpenMDAO.
- Arbitrary shape deformation of airfoils.
- Main and slat airfoil can be optimized within the same optimization.